WHITE PAPER FROM BLACK HOLES WORKSHOP (EDITED BY CON-X PROJECT)

Constellation-X and Black Hole Science

Team Leader: C. Reynolds (UMCP)
Team Members: A. Fabian (Black Holes panel chair), T. Yaqoob (JHU), R. Mushotzky (GSFC), M. Begelman (UC Boulder), J. Reeves (GSFC)

Black Hole Accretion and Strong Gravity

While the predictions of General Relativity (GR) have been verified in the weak-field limit, it has not been possible to perform the necessary quantitative experiments in the strong-field regime. This is a fundamental physics problem as GR is not a unique solution for the physics of gravity: until gravity can be studied experimentally in all of its applicable parameter space, alternatives cannot be eliminated.

Ever since the detection of rapid X-ray variability over 20 years ago, it has been clear that X-ray observations of accreting black holes provide a window on the immediate vicinity of the black hole event horizon. In the Chandra/XMM-Newton era (the first decade of the 21st century), X-ray studies of black holes have been refined to the point where we finally have well-understood, quantitative probes of strong gravity and the innermost, most highly energetic regions of their accretion flows. ***The innermost regions of accretion disks require X-ray studies, since the last signal we receive from accreted matter, at this innermost orbit, is also where the disk is hottest.***

The most powerful technique for inner accretion disk studies to date is the study of the broad iron fluorescence line seen in the X-ray spectrum of many accreting black holes (Tanaka et al. 1995). This line is emitted by the surface layers of the thin, Keplerian accretion disks believed to extend nearly down to the event horizon, and possesses a highly broadened and skewed energy profile sculpted by the effects of relativistic Doppler shifts and gravitational redshifts (see Figure 1).

Iron line spectroscopy with Chandra and XMM-Newton has enabled dramatic progress in understanding black hole systems, and robust examples of extremely broadened iron lines have been found in both stellar-mass and supermassive black hole systems. The highest quality X-ray data of some systems reveal extreme gravitational redshifts indicative of rapidly rotating black holes (Wilms et al. 2001, Fabian et al. 2002). In addition, the time-variable, quasi-periodic substructure seen in iron lines of some systems is likely to be a first glimpse of orbiting non-axisymmetric features in the inner accretion disk.

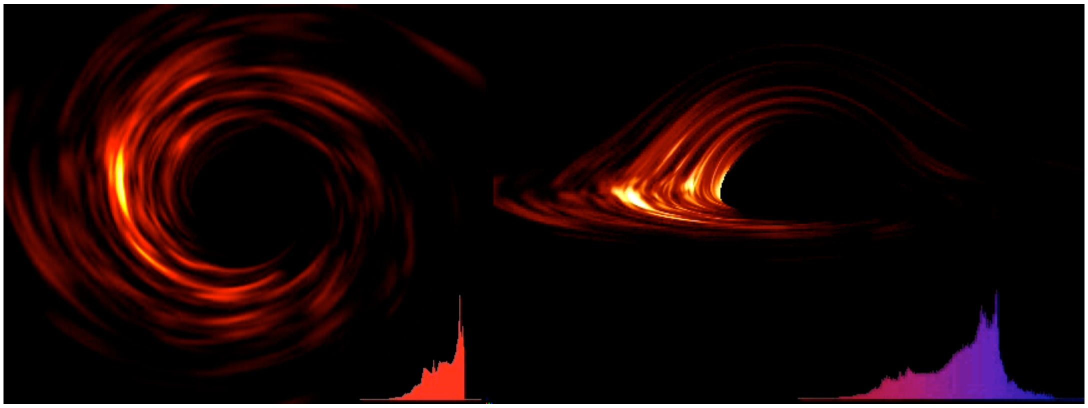

Figure 1: X-ray View of An Accretion Disk (Armitage & Reynolds 2003). View of the disk as seen by a distant observer at an inclination angle of 30º (left) and 80º (right). The inset in each panel shows the corresponding Fe K spectral line profile that will be observed by Constellation-X.

Despite the progress of recent years, we are hampered by the fact that several different models (e.g., models with different black hole spin parameters) can fit the same line profile. Since the line profiles we can study are temporally averaged over at least a few orbital periods of the innermost disk, they do not contain sufficient information to uniquely constrain both the space-time geometry and the accretion disk physics.

By sweeping away these limitations, Constellation-X will trigger a major qualitative leap in our understanding of strong gravity and accretion physics. Constellation-X, with its extremely high effective area and spectral resolution, will measure iron line profiles of the brightest AGN in a fraction of an orbit, allowing us to track individual orbiting substructures within the disk. We can determine the line profile over the light-crossing time of the system for the more massive AGN systems, which will allow us to search for reverberation effects of dramatic X-ray flares across the disk surface. Such direct probing of the propagation of the X-ray signal provides a fundamental constraint on the nature of space-time around the black hole (Young & Reynolds 2000).

The space-time metric in the strong gravity regime can be qualitatively mapped using the constraints noted above. A similarly fundamental investigation of black hole spin will also be carried out. Theory predicts that accretion of matter onto a black hole causes it to spin up (up to a maximum angular momentum), spinning space-time along with it. A major goal of the Constellation-X mission is to observe and quantitatively measure these effects, in particular to measure the black-hole spin with sufficient precision to rule out competing theories and investigate the relation between the spin and the properties of the black hole system (for example, why are the spins of galactic disks misaligned with the central black hole spin, and is there a similar misalignment in X-ray binary black holes and the orbital plane?).

Iron line studies by Constellation-X of the brightest AGN will allow us to calibrate time-averaged line profiles for measuring black hole spin. Further Constellation-X observations can then be used to measure the spin of any accreting black hole displaying this spectral feature, down to very faint flux levels. The result will be an explosion of knowledge about the distribution and demographics of black hole spin, which is crucial if we are to understand the origin and evolution of black holes of all masses.

In addition to exploring space-time geometry and black hole spin, Constellation-X observations of the innermost regions of black hole accretion flow will shed light on some of the most exotic phenomena in the current universe. These observations will probe the behavior of matter as it undergoes its final plunge into the black hole's event horizon and will investigate the possibility that the spin energy of the black hole is energizing the inner accretion disk and/or a relativistic jet. Finally, by looking at low-luminosity sources that possess rather "clean" environments, we will get our first detailed look at what are potentially the most powerful particle accelerators in the Universe.

From a General Relativity perspective, black holes have only two parameters: mass and angular momentum (significant charge cannot be sustained in a realistic astrophysical environment). While we cannot yet measure either of these with the precision that we can now measure cosmological parameters, ***the two Einstein Great Observatories, LISA and Constellation-X, will allow precision measurements of the two crucial black hole parameters (mass and angular momentum) in complementary ways.*** LISA will provide exquisite precision for a limited number of very special systems (stellar-mass black holes spiraling into 10^6 solar-mass black holes and mergers of supermassive black holes with masses $< 10^7$ solar masses). Constellation-X will measure mass and spin for a large number of accreting black holes, from stellar mass systems to the multi-billion solar mass black holes at the centers of giant elliptical galaxies. In addition, Constellation-X will further our understanding of how matter accretes onto a black-hole – a process which provides a huge, if not dominant, component of the radiant energy of the observable Universe.

AGN Outflows and the Circumnuclear Environment

Active galactic nuclei and quasars have been shown to harbor extremely powerful winds, with material ejected from their central engines at typical speeds 100-1000 km/s, and reported speeds as high as 50,000 km/s (Pounds et al. 2003, Reeves et al. 2003). The ejected matter is hot and has been either partially or fully ionized by the intense radiation from the central supermassive black hole and accretion disk. These AGN winds are part of "AGN feedback", whereby supermassive black holes may play a critical role in the evolution of their host galaxies. ***The rate at which mass is carried away by these winds appears to be as high as the rate at which mass is feeding the supermassive black hole*** (~0.01 to 1 solar masses per year). Why should mass be ejected from the central engine as fast as it is being consumed by the supermassive black hole? This profound puzzle has great impact on galaxy formation and the evolution of supermassive black holes.

Despite the large amounts of energy carried by these massive winds, we currently understand little about the mechanism for producing the outflows and how they are related to the black hole activity. The ejected mass eventually ends up in the intergalactic medium (IGM) and so has important implications for metal enrichment of the IGM.

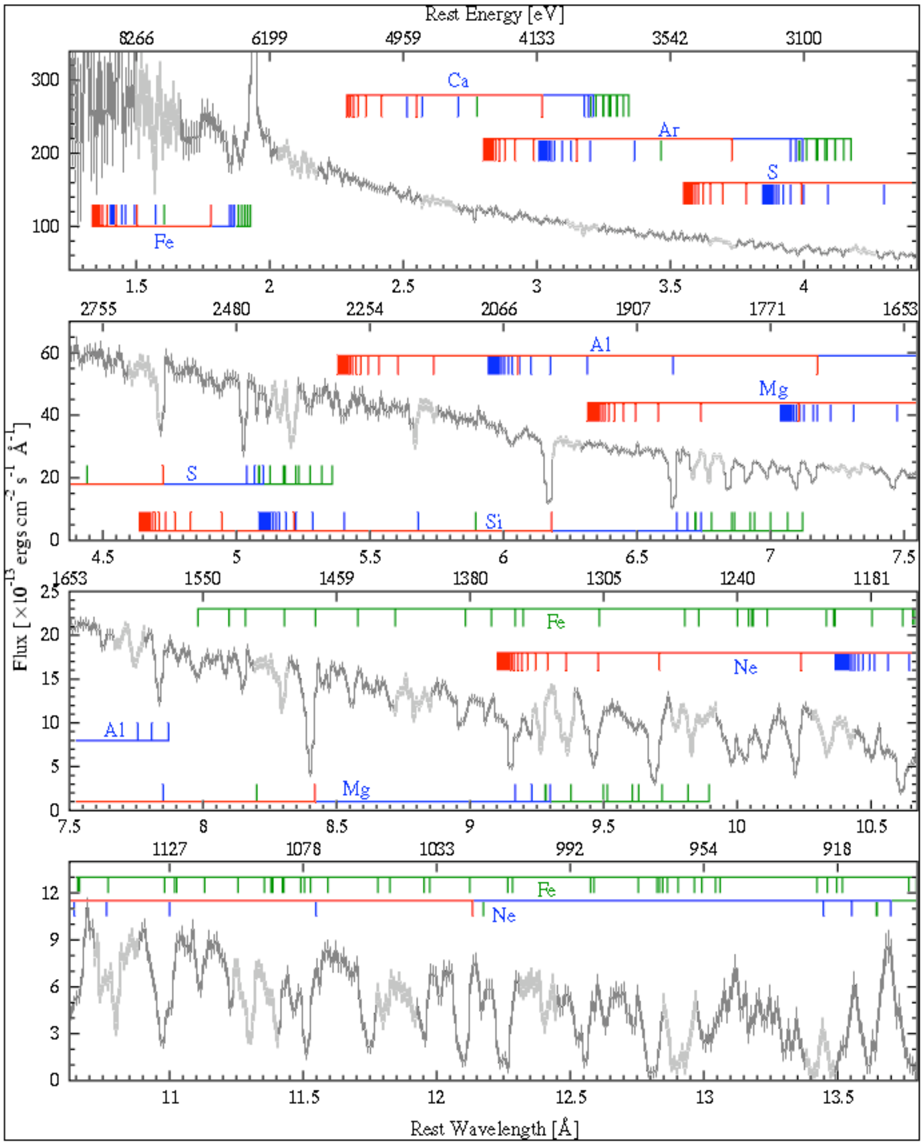

Figure 2: Chandra HETG spectrum of the Seyfert galaxy NGC 3783. This 900 ks observation demonstrates a complex velocity structure that will easily be observed with Constellation-X in 50-100 ks observations. (Kaspi et al. 2002)

Current data are ambiguous on the geometry of the outflows and measurements of key physical parameters such as density and location. The thermal and ionization state of the outflowing matter is also puzzling, because a single element can be found in a wide range of ionization states, requiring the matter to contain distinct components. In addition, some of those components can be kinematically distinct.

To enhance our understanding of these outflows we need a massive increase in throughput while maintaining or improving the spectral energy resolution (equivalently, the velocity resolution) compared to what is now available. The large throughput will both push variability studies to shorter timescales (probing finer structure) and enable the collection of a large sample or results with high enough signal-to-noise. Correlating the

X-ray measurements with other parameters (such as accretion rate and efficiency) will be critical for understanding the connection between the outflows and the central black hole and accretion disk.

Without coverage over a wide-enough range of ionization states of the light to heavier elements, there will always be ambiguity. In the soft X-ray band, where diagnostics using Oxygen, Neon and other light elements are important, gratings achieve the best velocity resolution. In the harder X-ray band, where Iron K-shell diagnostics are important, calorimeters achieve the best velocity resolution. Constellation-X is the only mission planned with both gratings and calorimeters to give it comparable velocity resolution in both the soft and hard X-ray bands with the required high throughput.

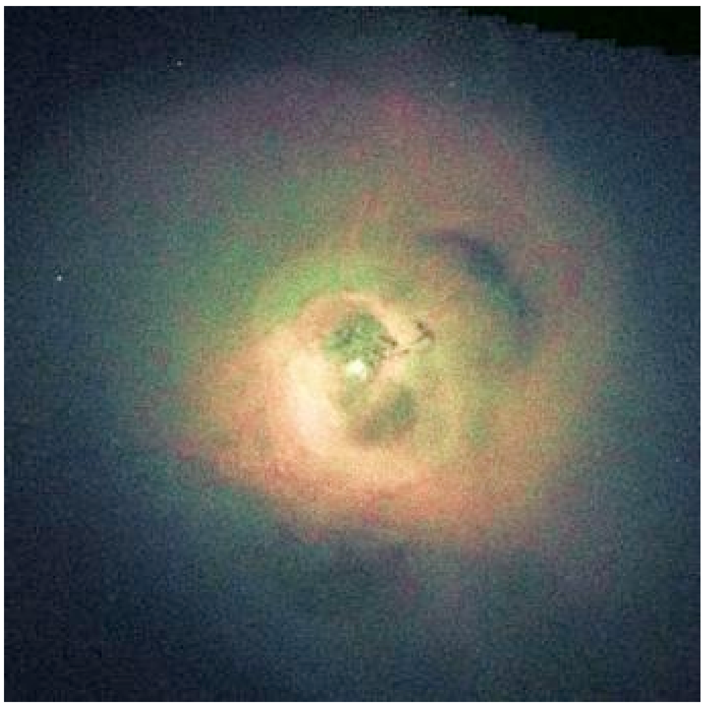

Figure 3: Chandra X-ray image of the cluster Perseus-A (Fabian et al. 2003). The central galaxy in this cluster, NGC 1275, is a radio source blowing radio "bubbles" into the intracluster medium. The image is 5.8' on a side. The Constellation-X field of view is quite important for this science, combined with <5" HPD PSF.

Black Hole Feedback and Structure Formation

Both Chandra and XMM have provided tantalizing clues that accreting black holes affect their environments out to extremely large distances (a megaparsec or more!) through the heating of intracluster or intergalactic medium (ICM/IGM). Dramatic progress has been made in determining the environmental impact of AGN in the cores of galaxy clusters. These are the monsters among the AGN wind sources, and theoretical calculations show that they may be the energetically most important factor in the evolution of the most massive galaxies in the Universe (e.g., White et al. 2004, Benson et al. 2003).

The intracluster medium (ICM) in the inner few hundred kiloparsecs of clusters (note that 3' corresponds to ~350 kpc at z~0.1) often has a cooling time much shorter than the Hubble time. This gas was expected to form a "cooling flow", slumping into the cluster core at rates of up to 1000 solar masses per year as it cools to very low temperatures. However, Chandra and XMM observations show that the ICM in such clusters only cools by a factor of about three between the outlying regions and the cluster core (Tamura et al. 2001; Peterson et al. 2001). Some agent must be heating the ICM core to prevent further cooling, and the prime candidate is an accreting supermassive black hole. Furthermore, intracluster gas is appreciably hotter than predicted by hierarchical clustering and gravitational collapse models, particularly in groups and small clusters (the "cluster entropy problem"); the most likely solution is energy injection by growing black holes.

The notion that black holes are heating the ICM is more compelling from the fact that black-hole/ICM interactions are clearly seen in Chandra data. The nature of these interactions is surprising, however. First, energy often seems to be added in a quiescent manner; evidence of strong shocks is lacking. For example, the rims surrounding the X-ray “cavities” in the Perseus cluster are colder than the ambient material, hence are not shocks driven by the expanding radio-lobes of Perseus-A (Fabian et al. 2003). Second, the existence of the cavities in the X-ray surface brightness suggests that the hot (possibly relativistic) fluid injected by the AGN does not mix well with the cluster gas. Rather than occurring via direct particle-particle interactions, the heating could occur through dissipation of the sound waves generated by the buoyant bubbles of relativistic fluid – these waves may already have been seen in Chandra observations Perseus and M87.

Can Constellation-X provide the "smoking gun" confirming AGN feedback on cluster scales? To image a large enough dynamic range of bubble structures at the distance of the Perseus cluster and map the innermost regions of nearby cluster cores requires a spatial resolution of ≥ 5 arcsec. A large collecting area is necessary, since the bubbles and related substructure have low contrast. In addition, a large field of view or scanning mode is needed to image bubbles and seek evidence of AGN-driven turbulence on the scales of the entropy problem (from a few hundred kiloparsecs to megaparsecs).

Velocity measurements will be important for establishing a connection between the mechanical heating phenomena and the AGN. With the microcalorimeter's spectral resolution (<4 eV), we can probe the ICM's velocity field to 200 km/s or less. We can also map the bubbles' velocity field and determine whether they are rising or expanding. AGN-induced turbulence in the ICM can be detected and spatially mapped. In addition, spectroscopy will offer measurements of abundance gradients, which can show the extent of entrainment by the rising bubbles, and information about the ionization mechanisms in the cluster gas that may reveal the role of, for example, cosmic rays in the ICM.

To date, cluster heating studies emphasize radio galaxies, which produce relativistic, collimated, low-density jets. But similar, perhaps larger, amounts of energy could emerge via denser, less collimated, subrelativistic winds – the same winds producing broad absorption line troughs in quasar spectra. Such winds are suspected to be more energetic than once thought, thanks to XMM observations of deep X-ray absorption.

References

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Observatory Specifications

The strong gravity and inner accretion-disk physics presented here do not require large fields of view, and the 15" HPD is more than sufficient. The main science driving parameters are collecting area and spectral resolution as detailed in the table below.

For the radio galaxy/cluster studies, the field of view requirement is >3×3 arcminutes, and PSF requirement is <5" HPD, which is driven by the scale of interaction between the radio jets and the intracluster medium.

	Spatial Res.	**Energy Res.**	**Eff. Area (@ 6 keV)**	**FOV**
Orbiting substructure on inner disk		100 @ 6 keV	3000	
Relativistic reverberation from disk		100 @ 6 keV	15000	
Separating disklines & very complex absorption		1000 @ 6 keV	1000	
Detailed study of AGN wind (warm absorber)		1000 @ 0.5-8 keV	3000	
Velocity field of AGN/ICM interaction	< 5 arcsec	1000 @ 6 keV	6000	3×3 acrmin

Discussion of Effective Area Needs for Reverberation Mapping

The baseline design for Constellation-X (0.6 m^2 at 6 keV) assumes reverberation studies of nearby bright Seyfert 1's with 10^8 solar-mass black holes. With Chandra, XMM-Newton, and optical studies in the last several years, we have learned that Seyfert 1's likely have *lower* mass black holes (by factors of 3-10). This indicates that the effective area should be *larger* by the same factor to ensure reliable reverberation mapping studies of Seyfert 1 black holes. Since it may be that the source geometry is more conducive to reverberation mapping than generally assumed (cf A. Fabian's work), rather than demand 10× the previous area, 3× is likely sufficient. A reasonable estimate of the effective area need is 1.5 m^2 at 6 keV in order to do the full-up relativistic reverberation analysis of the type outlined in Young and Reynolds (2000).